

# Formation of the Double Neutron Star System PSR J1930–1852

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## ABSTRACT

The spin period (185 ms) and period derivative ( $1.8 \times 10^{-17} \text{ s s}^{-1}$ ) of the double neutron star (DNS) system PSR J1930–1852 recently discovered indicate that the pulsar was mildly recycled through the process of Roche-lobe overflow. This system has the longest orbital period (45 days) of the known DNS systems, and can be formed from a helium star-NS binary if the initial mass of the helium star was  $\lesssim 4.0 M_{\odot}$ ; otherwise the helium star would never fill its Roche-lobe (Tauris et al. 2015). At the moment of the supernova explosion, the mass of the helium star was  $\lesssim 3.0 M_{\odot}$ . We find that the probability distribution of the velocity kick imparted to the new-born neutron star has a maximum at about  $30 \text{ km s}^{-1}$  (and a tail up to  $260 \text{ km s}^{-1}$ ), indicating that this NS most probably received a low kick velocity at birth.

*Subject headings:* stars: evolution – stars: neutron – pulsars: individual (J1930–1852) – binaries: general

## 1. Introduction

The formation of double neutron star (DNS) systems is believed to be the endpoint of massive binary evolution (e.g., Bhattacharya & van den Heuvel 1991; Tauris & van den Heuvel 2006). Generally a massive binary first evolves into a high-mass X-ray binary (following the formation of the first NS) and then evolves through a spiral-in (common-envelope) phase into a helium star plus NS binary (e.g., van den Heuvel & De Loore 1973). When the helium star explodes as a supernova (SN) to become the second NS, the final binary may be a DNS system.

Most DNS systems share the characteristics of relatively short spin periods (22.7 – 104 ms), short orbital periods (0.1 – 18.8 days), and eccentric orbits. However, PSR J1930–1852,

a DNS system recently discovered by Swiggum et al. (2015), has an orbital period as long as 45 days and a relatively long spin period of 185 ms. In this paper, we will discuss the formation history of this system from helium star-NS binaries.

## 2. Formation of PSR J1930–1852

### 2.1. Constraints on the parameter space of the helium star-NS binaries

Evolutionary calculations of helium star-NS binaries have performed by many authors (e.g., Dewi et al. 2002; Dewi & Pols 2003; Ivanova et al. 2003; Tauris et al. 2015). During core helium burning and further burning phases, the helium star loses mass through stellar winds (Hamann et al. 1995). Of particular interest are low-mass ( $\lesssim 3.5M_{\odot}$ ) helium stars since they swell up to large radii during their late evolution (Paczynski 1971; Nomoto 1984; Habets 1986). The expansion of the helium star may finally result in the occurrence of Roche-lobe overflow (RLOF) and mass transfer. The NS can be recycled by accretion of mass and angular momentum from the helium star companion. If the binary orbit is very wide or the helium star is too massive, mass transfer via ROLF will not occur prior to the SN explosion. For PSR J1930–1852, the measured spin period and period derivative give a relatively weak surface magnetic field of  $6 \times 10^{10}$  G, implying that the pulsar was mildly recycled during the previous mass transfer phase (Tauris et al. 2015).

In Fig. 1 we show the plausible distribution of the helium star-NS binary in the final mass ( $M_{\text{He,f}}$ ) of the pre-SN helium star vs. the pre-SN orbital separation ( $a_0$ ) plane.

The pre-SN orbital separation  $a_0$  should lie between the periastron and apastron of the post-SN orbit with a separation of  $a$  (Flannery & van den Heuvel 1975), i.e.,

$$a(1 - e) \leq a_0 \leq a(1 + e), \quad (1)$$

where  $e$  is the post-SN eccentricity. In Fig. 1 we indicate the maximum and minimum pre-SN orbital separations with the two black solid lines by adopting  $a = 73R_{\odot}$  and  $e = 0.4$ .

The fact that PSR J1930–1852 has experienced mass transfer in a wide orbit indicates that  $M_{\text{He,f}} \lesssim 3M_{\odot}$  as indicated by the blue dashed line in Fig. 1, which distinguishes whether the helium star can evolve to fill its RL. For a system with a wide orbit at the time of the SN explosion, the preceding mass transfer should have decreased the orbital separation, so the initial separation can have been wider as indicated by the blue dotted line in Fig. 1. The calculated results of Tauris et al. (2015, see their Table 1) were used to plot these two lines. From this figure we can estimate that the initial mass of the helium star is  $\lesssim 4M_{\odot}$ .

## 2.2. Asymmetric SN explosions and NS kicks

When the helium star exploded as a SN, a kick velocity  $V_k$  was imparted to the second NS. The orientation of the kick velocity is controlled by the angles  $\theta$  and  $\phi$ , as shown in Fig. 2. Here  $\theta$  is the angle between the kick velocity and the pre-SN orbital velocity  $V_0$ , and  $\phi$  is the positional angle of the kick velocity with respect to the orbital plane. Thus the relation between  $a_0$  and  $a$  is given by (Hills 1983; Dewi & Pols 2003),

$$\frac{a_0}{a} = 2 - \frac{M_0}{M}(1 + \nu^2 + 2\nu \cos \theta), \quad (2)$$

where  $M_0 = M_1 + M_{\text{He,f}}$ ,  $M = M_1 + M_2$ ,  $\nu = V_k/V_0$ , and  $V_0 = (GM_0/a_0)^{1/2}$ ;  $M_1$  and  $M_2$  are the pulsar mass and the second NS mass respectively. We assume  $M_1 = M_2 = 1.3M_\odot$  in the following calculation. The eccentricity of the post-SN orbit can be written as (Hills 1983; Dewi & Pols 2003)

$$1 - e^2 = \frac{a_0}{a} \frac{M_0}{M} [1 + 2\nu \cos \theta + \nu^2 (\cos^2 \theta + \sin^2 \theta \sin^2 \phi)]. \quad (3)$$

In Eqs. (2) and (3) there are five variables, that is,  $V_k$ ,  $M_{\text{He,f}}$ ,  $a_0$ ,  $\theta$ , and  $\phi$ . We can derive useful information on the distribution of  $V_k$  if the values of  $M_{\text{He,f}}$  and  $a_0$  are reasonably constrained.

From Eqs. (2) and (3), the condition of  $\sin^2 \phi = 1$  always gives the solution  $a_0 = a(1 \pm e)$ , independent of the magnitude of the  $V_k$ . This result corresponds to the lower and upper limits of the orbital separation, as given by Eq. (1). For the case of  $\sin^2 \phi = 0$ , we can derive two boundary lines for any specific value of  $V_k$ . In Fig. 1, the orange and green lines correspond to the  $V_k = 30$  and  $50 \text{ km s}^{-1}$ , respectively. In a special situation that a new born NS has no kick ( $V_k = 0$ ), there are two solutions with  $M_{\text{He,f}} = 2.34M_\odot$ ,  $a_0 = 43.8R_\odot$  and  $M_{\text{He,f}} = 0.26M_\odot$ ,  $a_0 = 102.2R_\odot$ .

For any fixed value of  $V_k$ , the possible values of  $M_{\text{He,f}}$  and  $a_0$  are confined by the conditions of  $\sin^2 \phi = 0$  and  $\sin^2 \phi = 1$ . As an illustration, Fig. 3 shows the allowed distribution of  $M_{\text{He,f}}$  and  $a_0$  with  $V_k = 40 \text{ km s}^{-1}$ . The thick green and red lines show the solutions in the limits of  $\sin^2 \phi = 0$  and 1, respectively. We set 1000 random values for both  $\theta$  and  $\phi$  in the interval of  $0 - \pi$ , and plot the solutions in Fig. 3 as triangles.

Habets (1986) suggested that the threshold mass for a single helium star to produce a NS is  $\sim 2.2M_\odot$ . If the helium star is in a binary, the threshold mass is determined by the CO or ONeMg core mass (Nomoto 1984). Here we assume that the minimal mass of a pre-SN helium star is  $1.4M_\odot$ , which is compatible with the calculated results of Tauris et al. (2015), while the pre-SN maximal mass is  $\sim 3M_\odot$  (see Section 2.1). We ran millions

of numerical calculations with randomly distributed angles  $\theta$  and  $\phi$ . Using the limits of  $1.4M_{\odot} \leq M_{\text{He,f}} \leq 3M_{\odot}$  and Eq. (1), we derived the distribution of the kick velocities. Figure 4 shows the normalized and accumulated distributions of  $V_k$  with the black and red curves, respectively. We find that the  $V_k$ -distribution has a peak at  $\sim 30 \text{ km s}^{-1}$  with a maximum value  $\sim 260 \text{ km s}^{-1}$ . For  $V_k \leq 50$  and  $100 \text{ km s}^{-1}$ , the generated probabilities in our calculations are 0.63 and 0.77, respectively. In order to reproduce the observed parameters of PSR J1930–1852, the higher the value of  $V_k$ , the more restricted the orientation of the NS kick. We therefore see that the most likely value of  $V_k$  was low, of the order of  $30 \text{ km s}^{-1}$ .

### 3. Summary

Our analysis reveals the following results.

(i) To satisfy the condition that there was ROLF-mass transfer in the progenitor helium star-NS binary with a wide orbit, the mass of the pre-SN helium star  $M_{\text{He,f}}$  should be  $\lesssim 3.0M_{\odot}$  and correspondingly the initial mass  $\lesssim 4M_{\odot}$ .

(ii) For randomly orientated NS kicks, the most likely values of the kick velocities are low with a peak at  $\sim 30 \text{ km s}^{-1}$ .

Recently Beniamini & Piran (2015) demonstrated that the second collapse in the majority of DNS systems involved small mass ejection ( $\Delta M \lesssim 0.5M_{\odot}$ ) and a low kick velocity ( $V_k \lesssim 30 \text{ km s}^{-1}$ ), which may be related to the electron-capture SNe as suggested by Podsiadlowski et al. (2004) and van den Heuvel (2004). For the helium star-NS progenitor of PSR J1930–1852, both the helium star’s mass and the kick velocity are relative low, which are indeed likely to correspond with the second NS having originated from an electron-capture SN. Still the formation channel of core-collapse SN can not be excluded, and further observations can help settle this problem.

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### REFERENCES

- Beniamini, P. & Piran, T. 2015, arXiv: 1510.03111
- Bhattacharya, D., & van den Heuvel, E. P. J. 1991, Phys. Rev., 203, 1

- Dewi, J. D. M., Pols, O. R., Savonije, G. J., & van den Heuvel, E. P. J. 2002, MNRAS, 331, 1027
- Dewi, J. D. M., & Pols, O. R. 2003, MNRAS, 344, 629
- Flannery B. P., & van den Heuvel E. P. J. 1975, A&A, 39, 61
- Habets, G. M. H. J. 1986, A&A, 167, 61
- Hamann, W.-R., Koesterke, L., & Wessolowski, U. 1995, A&A, 299, 151
- Hills, J. G. 1983, ApJ, 267, 322
- Ivanova, N., Belczynski, K., Kalogera, V., Rasio, F. A., & Taam, R. E. 2003, ApJ, 592, 475
- Nomoto, K. 1984, ApJ, 277, 791
- Paczynski, B. 1971, Acta Astro., 21, 1
- Podsiadlowski, P., Langer, N., Poelarends, A. J. T., Rappaport, S., Heger, A., & Pfahl, E. 2004, ApJ, 612, 1044
- Swiggum, J. et al., 2015, ApJ, 805, 156
- Tauris, T. M., & van den Heuvel, E. P. J. 2006, in Compact Stellar X-Ray Sources, ed. W. H. G. Lewin & M. van der Klis (Cambridge: Cambridge Univ. Press), 623
- Tauris, T., Langer, N., & Podsiadlowski, Ph. 2015, MNRAS, 451, 2123
- van den Heuvel, E. P. J., & De Loore, C. 1973, A&A, 25, 387
- van den Heuvel, E. P. J. 2004, Proceedings of 5th INTEGRAL Workshop, ESA SP-552, Eds. V. Schoenfelder, G. Lichti and C. Winkler. (ESA Publ. Div. ESTEC, Noordwijk), 185

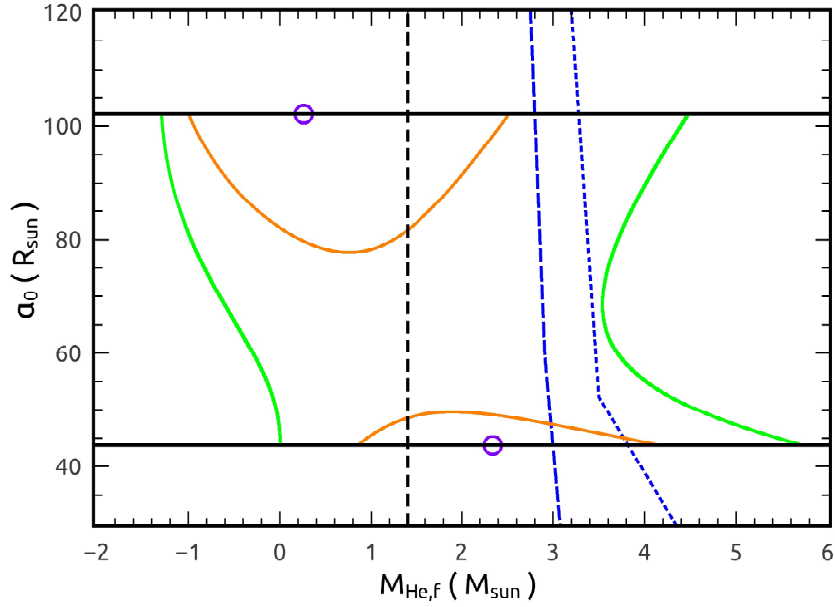


Fig. 1.— The allowed distribution of the pre-SN helium star mass  $M_{\text{He},f}$  and the orbital separation  $a_0$ . The blue dashed line distinguishes whether the helium star can fill its RL prior to the SN explosion, and the blue dotted line denotes the corresponding relation at the beginning of binary evolution with an unevolved helium star (Tauris et al. 2015). The pre-SN orbital separation of PSR J1930–1852 is limited by the two black solid lines. The orange and green lines correspond to the solutions of Eqs. (2) and (3) when  $\sin^2 \phi = 0$  in the cases of  $V_k = 30$  and  $50 \text{ km s}^{-1}$ , respectively. The two circles mark the positions when no kick is impacted to the second NS. The minimal mass of  $1.4M_{\odot}$  for the helium star is presented with the dashed black line.

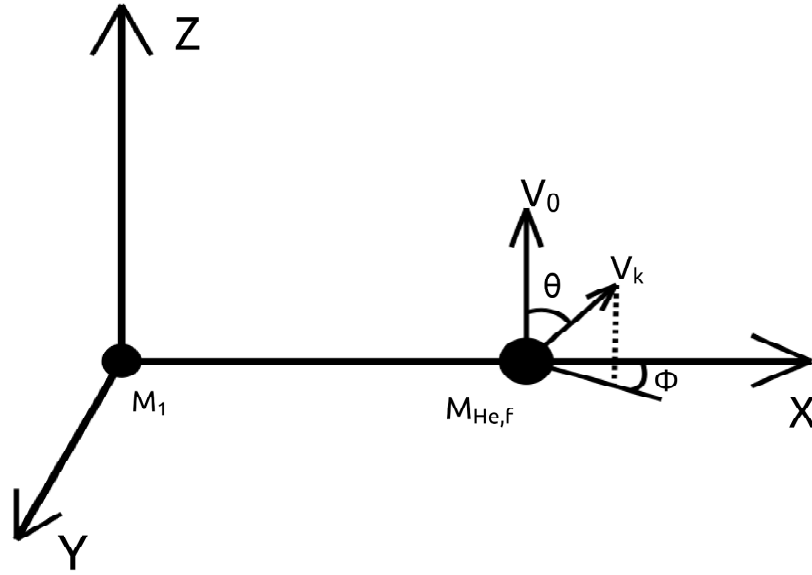


Fig. 2.— The orientation of the kick velocity relative to the original orbital velocity and the orbital plane of a helium star-NS binary.

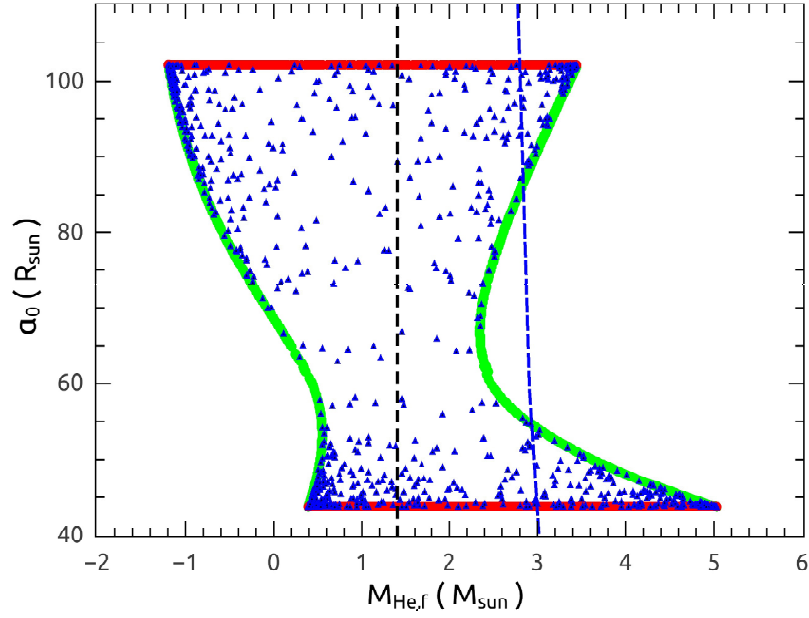


Fig. 3.— The distribution (blue triangles) of the calculated  $M_{\text{He,f}}$  and  $a_0$  from Eqs. (2) and (3) with randomly distributed angles  $\theta$  and  $\phi$ . Here  $V_k$  is set to be  $40 \text{ km s}^{-1}$ . The thick green and red lines correspond to the cases of  $\sin^2 \phi = 0$  and 1, respectively. The thin dashed lines have the same meanings as in Fig. 1.



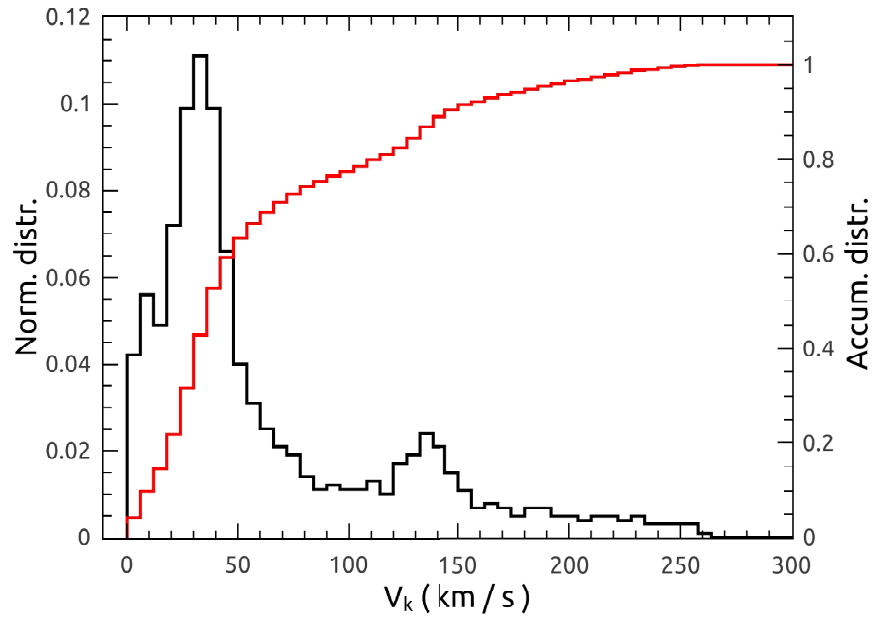


Fig. 4.— The normalized (black line) and accumulated (red curve) distributions for the calculated kick velocities.